

Relativity Is Not About Spacetime

Edward J. Gillis*

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Abstract

Quantum measurement predictions are consistent with relativity for macroscopic observations, but there is no consensus on how to explain this consistency in fundamental terms. The prevailing assumption is that the relativistic structure of spacetime should provide the framework for any microphysical account. This bias is due, in large part, to our intuitions about local causality, the idea that all physical processes propagate through space in a continuous manner. I argue that relativity is not a guarantor of local causality, and is not about ontological features of spacetime. It is, rather, an expression of the observational equivalence of spacetime descriptions of physical processes. This observational equivalence is due to the essentially probabilistic nature of quantum theory.

1 Relativity Is Not Based On Local Causality

In order to get from here to there, you have to pass through points in between. This intuitively obvious notion is fundamental to the implicit model of the external world that shapes our thoughts and actions. Other vertebrate species also exhibit behavior that appears to be guided by analogous cognitive processes. I recall watching the children of some friends use a laser pointer to tease their cat. They would shine the laser spot on the floor in front of the cat, move it around enough to get the cat's attention, and induce her to start tracking it. They would then jerk the spot of light to a completely different place in the room, leaving the pet totally bewildered after witnessing a seemingly coherent object jump discontinuously through space.

The expectation that things move through space in a continuous fashion is very deeply ingrained. Developmental psychologists have attempted to determine to what extent it might arise from innate neural processes.¹ No matter what one thinks about the relative contributions of heredity and learning in generating this belief, it clearly plays an enormous role in guiding our everyday life and in the ways that we think about physics.

*email: gillise@provide.net

¹See, for example, *Spatiotemporal continuity and the perception of causality in infants*, by Leslie[1].

Its place in our world view and its influence on the rise of modern science are evident in Newton's efforts to justify and reconcile gravitational action at a distance with the received belief that causes are transmitted by contact through some medium. It is not completely certain how he thought that the reconciliation was to be achieved, but he clearly acknowledges the prevailing notion in his 1693 letter to Bentley[2]:

"...That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it."

The success of Newton's theories of mechanics and gravitation led people to accept the idea of action at a distance, at least provisionally. However, the intuition that all processes must propagate in a continuous manner is so compelling that the principle of local causality gradually reasserted itself in physics. The concept of gravitational potential, employed by Euler, Lagrange, and Laplace hints at the idea of a field defined at all points in space. In the nineteenth century, the work of Faraday and Maxwell fully established the idea of continuously propagating electromagnetic fields, and suggested to some the existence of a luminiferous ether. It also led to a clear conflict with Newtonian mechanics, which was resolved by Einstein's Special Theory of Relativity.

Einstein's theory revolutionized our ideas about time, with radical consequences for the concepts of mass, motion, and energy. However, it also reestablished physics on the venerable principle of local causality. In this respect, it was a very conservative revolution.

Einstein apparently cemented the triumph of this traditional principle with the development of the General Theory of Relativity, which is able to explain the propagation of gravitational influences in a locally causal manner.

Quantum mechanics was developed at roughly the same time as the theories of relativity. Although he made major contributions to its development, Einstein was unhappy with some of the central features of quantum theory, in particular, its probabilistic nature. In his paper with Podolsky and Rosen[3] he argued that some of the predicted correlations for entangled systems would require 'spooky action at a distance', if one assumed that the effects were truly nondeterministic. The conclusion drawn in the EPR paper was that quantum mechanics needed to be 'completed' by a fully deterministic theory.

Bell turned the EPR argument around[4, 5]. He showed that the correlations between some specific pairs of outcomes of spacelike-separated measurements on entangled particles are too large to be explained by the assumption that the results are determined by some factors in the common past of the measured systems.² These

²Aside from superdeterministic explanations.

nonclassical "super" correlations appear to indicate that the particular result of one of the measurements acts across a spacelike interval to change the probabilities of the outcomes of the other measurement. There are real superluminal effects.

So why cannot these effects be used to send superluminal signals? The reason is that one cannot control the outcomes of the local measurement. They are *essentially probabilistic*. When all of the possible results are summed over, the total probability of any particular distant outcome is unchanged. It is a striking result that the Born probability rule[6], and *only the Born probability rule*, is able to maintain this consistency. Any slight deviation from it would enable superluminal information transmission. It is not hard to see this, given a sufficient number of identically prepared entangled systems. This is, of course, also a consequence of Gleason's theorem[7].

This situation is sometimes described as demonstrating the "peaceful coexistence" of quantum theory and relativity[8, 9]. In a number of commentaries, it even seems to take on a rather miraculous air. But, is it not much more straightforward to assume that the impossibility of sending superluminal signals, and, *hence, relativity*, is a consequence of the fundamentally probabilistic nature of the elementary interactions that constitute measurements?

Note that the same line of argument that shows how the Born rule prevents superluminal signalling also shows that it is impossible to say which of the two (or more) measurements is affecting the other. In other words, there is no *observable* sequence of these spacelike-separated events. This is one of the fundamental characteristics of the relativistic description of spacetime.

Einstein and his colleagues set out to show that if physical theory retained its non-deterministic elements, it would have to countenance nonlocal actions. Bell showed that the inclusion of nonlocal effects is unavoidable, and subsequent analysis[10, 11, 12, 13] has demonstrated that the nondeterministic nature of these effects is essential to the prevention of superluminal signalling. It is ironic that relativity is preserved by the very property of quantum theory that Einstein found so disturbing - indeterminism.

2 Making Sense of Signal Causality

We have misunderstood what relativity is really about. This is a result of the historical path to its discovery, our pretheoretic biases, and the elegance of the theory. Its two great classical instantiations, Maxwell's electromagnetism and general relativity, capture our intuitions about continuous propagation so beautifully that we perceive local causality as a manifestation of the metric structure of spacetime. This perception fosters an attitude that, no matter how serious a problem is, any proposed solution should fit comfortably within this structure.³ However, even without taking into account the challenges posed by quantum theory, there are reasons to question

³At least until we approach the Planck scale

the completeness of the classical relativistic world view. The infinite self-energy and radiation reaction problems of electrodynamics have provoked proposals that violate conventional notions of causality[14]. Solutions of Einstein's gravitational equation that approximately describe our universe exhibit generic singularities, where space-time and the laws of physics break down[15]. Since physicists have worked on these issues for roughly a century, one might start to wonder whether there are inherent logical limits to the notion of local causality, analogous to the limits on provability in mathematics.⁴

In any case Bell's analysis has forced us to recognize that not everything that happens in our world can be explained in terms of locally propagating processes. The fact that local causality is not the basis for contemporary physics is often obscured by a failure to distinguish between it and the weaker, more general notion of signal causality, the prohibition of superluminal information transmission. Local causality implies signal causality, but signal causality permits superluminal effects, provided that they are nondeterministic, and in accord with the Born rule.

This more general principle is implemented in quantum field theory as the requirement that spacelike-separated field operators commute[16]. This means that a measurement made in one location cannot affect the overall probabilities of possible outcomes of a measurement made in a spacelike-separated region, even though specific pairs of outcomes exhibit correlations that indicate some kind of linkage across the spacelike interval between them.

Most quantum field theory texts describe the commutativity requirement as a causality condition, usually without qualifying it as *signal* causality. In his book, Weinberg[17] adopts a somewhat different perspective:

"The point of view taken here is that [the commutativity requirement] is needed for the Lorentz invariance of the S-matrix, without any ancillary assumptions about ... causality."

One might say that while most authors take the requirement as a formal expression of causality, Weinberg prefers to view it as preserving relativity. These complementary interpretations highlight the intimate connection between the two principles. It must be emphasized, however, that the attribution of Lorentz invariance to the S-matrix does *not* automatically assign some special ontological status to the Lorentz-invariant metric of Minkowski spacetime. The S-matrix is a set of theory-laden calculations, and it reflects a number of properties of the mathematical formalism. If the metric properties of spacetime alone were sufficient to guarantee the Lorentz invariance of observable quantities, there would be no need for a special postulate to govern the action of field operators. This additional assumption is aimed at regulating the nonlocal effects that are implicit in quantum theory.

⁴This is only an analogy. I am not suggesting that quantum indeterminism is logically linked to Goedel's incompleteness theorem

The S-matrix calculations yield probabilities for measurement outcomes. These quantities are compared to readings of macroscopic laboratory instruments, and the meaning of the commutativity requirement in relation to them is clear. However, problems arise when we try to translate the commutativity condition into a statement about *fundamental physical processes*.

This translation problem derives from the way in which contemporary physical theory is structured. Dynamic equations describing elementary processes are completely deterministic. Nonlocal, probabilistic effects have been banished to a lawless, ill-defined border region that lies somewhere between microscopic and macroscopic realms. This theoretical structure has been incredibly fruitful, but it has also made it incredibly difficult to understand what it is saying about the world at the most fundamental level.

This is why Bohr thought that references to macroscopic, classical concepts are essential to interpret statements about microphysical processes[18, 19]. Bell described the problem very eloquently[20]:

”More importantly, the ‘no signalling...’ notion rests on concepts which are desperately vague, or vaguely applicable. The assertion that ‘we cannot signal faster than light’ immediately provokes the question:

Who do we think *we* are?

We who can make ‘measurements’...?... chemists, or only physicists,...pocket calculators, or only main frame computers? ”

Bell raised the possibility that the relation of signal causality to elementary processes is analogous to that of thermodynamics, but he did not think that this was a promising approach.

Maudlin[21] has extended Bell’s critique. After acknowledging that the notion of ‘signalling’ apparently makes essential reference to human activity, he demonstrates that the Born probability rule precludes the use of nonlocal quantum effects for this purpose. However, he goes on to argue that the nonlocal changes in the states of elementary systems do imply some sort of superluminal transmission of information to *that particular* system, even though the information is not, in general, accessible to any other physical system.

The criticisms of Bell and Maudlin have considerable merit, and they pose a serious problem for the concept of signal causality. It appears that when we formulate it in terms of elementary physical processes (rather than human activities) as a prohibition of superluminal information transmission, it does not really apply to the kinds of nonlocal quantum effects that we are trying to describe.

To deal with this problem I will try to show that, despite Bell’s reservations, the relationship of signal causality to elementary processes *is* analogous to that of thermodynamics by noting some important parallels between the concepts of ‘temperature’ and ‘information’. The concept of information that I will use is distinct from that of Maudlin. It will allow us to define signal causality as the prohibition of

superluminal information transmission, and it will depend in an essential way on the nondeterministic nature of elementary processes.

When we say that the temperature in a room is 20° C, we are implying a great deal about conditions in the room. For example, the room is in thermal equilibrium - no significant net transfers of energy will take place between adjacent masses of air. Individual molecules do not have temperatures. They can have almost any energy, and in a collision with another molecule there is an overwhelming likelihood that a substantial amount of energy will be exchanged. The concept of temperature applies to very large collections of molecules that meet the proper conditions. Of course, the term 'temperature' is sometimes applied to individual elementary particles as a synonym for 'energy'. There is an important link between energy and temperature, but, as just noted, the ascription of a definite temperature implies a number of relationships among physical systems.

I maintain that Maudlin's application of the term 'information' to individual elementary systems is analogous to ascribing a temperature to a single molecule. What Maudlin means by 'information' is a full specification of the parameters required to characterize an elementary state. This is a perfectly reasonable use of the term, depending on the circumstances, just as talking about the 'temperature' of individual particles makes sense in certain contexts. But, as Maudlin emphasizes, this 'information' is not accessible to any other physical systems.

The concept of information is, to a large extent, relational. Physical systems that can instantiate information must be able to represent the states of other systems, and to transmit and receive the relevant types of representations. Maudlin's inaccessible information clearly lacks these attributes.

To obtain information about the state of a physical system one induces it to interact with other particles in such a way that correlations are established between the states of the subject and detector systems. A chain or cascade of correlating interactions is set up so that the state of the original subject can be represented in a much larger system. If these interactions were completely deterministic and reversible, one could generate a complete description of the original state. The reason that we cannot, in general, obtain such a description is that the elementary interactions that establish correlations between subject and detector particles *are not completely deterministic*.

If we explicitly recognize the nondeterministic behavior at the level of elementary processes, we can understand why information cannot be transmitted superluminally. Individual elementary particles can possess a definite state, but they cannot, by themselves, instantiate information about that state because interactions with other particles can change the state in a nondeterministic way. There would then be no faithful, physical representation of the original state. This is the content of the No-cloning theorem[22]. The preparation of individual particles in definite, known states requires interaction with very large numbers of other particles. It is only at this scale, through the full network of correlations that are established, that information

can be said to exist. Information about a physical system must be fully accessible to other systems, and it must be reasonably stable against probabilistic changes. This means that the definition of physical information is a matter of gradation or degree; but it is still a perfectly objective concept. It is analogous to temperature, which is perfectly well-defined, even though we do not precisely specify how big a system must be to achieve thermal equilibrium.

The point is that the limitations on information and on its transmission are explainable in terms of a basic property of elementary interactions - their probabilistic nature. As stated above, this issue has been clouded by the fact that contemporary theory does not acknowledge any deviation from complete determinism at this level. There are a number of reasons for this, but the biggest one is that such an acknowledgement completely disrupts our understanding of spacetime structure.

3 The Status of Spacetime Structure

It is possible to describe nondeterministic behavior at the level of elementary interactions, at least in a phenomenological way. The linearity of the Schrödinger equation permits nonlocal, probabilistic transfers of amplitude between interacting and non-interacting branches of the wave function without violating signal causality. The details have been given elsewhere[23]. The catch is that these hypothesized effects are both nonlocal and nondeterministic. Nondeterminism entails irreversibility, and irreversibility implies that the effects must be sequenced. If interactions involving the same entangled system occur in spacelike-separated regions, there is no way to account for the sequencing of the nonlocal effects associated with the interactions simply by reference to the relativistic metric structure.

This apparent conflict with relativity is present in conventional descriptions of quantum measurement. To see this assume that the wave function of a single particle has bifurcated into two main branches, and that there is an ideal detector in the path of each branch. One of the detectors registers the presence of the particle; the other does not. Suppose that the two measurements are spacelike-separated. In some reference frames the positive outcome occurs first; in others the negative outcome occurs first. The two different sequences are associated with two distinct accounts: (1) the positive outcome collapsed the wave function, setting the amplitude of the alternate branch to zero, insuring a negative outcome for the other measurement; (2) the negative outcome collapsed the wave function so that all of the amplitude was concentrated in the other branch, insuring a detection.

Each of these sequences consists of a nondeterministic, irreversible event followed by a deterministic, reversible one. The problem is that the order is switched, with the positive outcome first in one account, and the negative outcome first in the other⁵. The descriptions are *observationally equivalent, but logically incompatible*. To deal

⁵Treating the events as simultaneous does not work. See [23].

with this conundrum many try to interpret quantum wave functions in a purely epistemic way, but this approach is fraught with difficulties.

Conventional theory deals with this conflict by completely obscuring the boundary between deterministic and nondeterministic effects. There is a better way. The non-deterministic character of the effects, with its attendant irreversibility, is the source of the problem, but it also provides the solution. In the same way that it prevents acquisition of precise information about the state of individual elementary systems, it also precludes detection of the *sequence* of spacelike-separated nonlocal effects.

To see this consider two particles in an entangled state, $\alpha|x_1\rangle|x_2\rangle + \beta|y_1\rangle|y_2\rangle$, with $|x\rangle$ and $|y\rangle$ orthogonal. Suppose that they separate to a macroscopic distance where they each encounter a series of 'detector' particles arranged to interact with the $|x\rangle$ branch. In [23] it was proposed that each such entangling interaction is accompanied by a small, probabilistic nonlocal shift of squared amplitude either from the interacting ($|x\rangle$) branch to the noninteracting ($|y\rangle$) branch of the wave function, or vice versa. Assume that the magnitude of the shifts of squared amplitude is 0.01. The state must be well defined at each stage of the process, so it is necessary to assume that the spacelike-separated interactions involving the left and right moving particles are sequenced in some fashion. Suppose that initially, we have $\alpha\alpha^* = \beta\beta^* = 0.5$. Imagine that after several hundred interactions have occurred on the left side, we take a "God's eye" view of the quantum state. If the sequencing of right and left side interactions is random, then we would expect that the nonlocal transfers from several hundred right side interactions would have also affected the state up to this point. Suppose that $\alpha\alpha^*$ is now 0.75. On average this would mean that about $25^2 = 625$ transfers have occurred. The point is that this state is the *only physical record of the sequence of nonlocal effects*, and it is perfectly consistent with over 2^{300} different sequences. If we were to add some other kinds of interactions to "watch" the process we would introduce additional entangling interactions with additional nondeterministic effects. There is no way to record which one of the enormous number of possible sequences actually occurred. They are observationally equivalent.

Relativity should be understood as a statement of this observational equivalence, and, to a large extent, as a consequence of the inherently nondeterministic nature of elementary interactions. The nondeterminism entails limits on the kinds of information that can be instantiated in physical systems, and so it regulates the ways in which information can be transmitted. Relativity does *not* rule out either nonlocal effects or the sequencing of those effects. It is an expression of the fact that there can be no physical record of such sequencing.

Our view of the status of spacetime structure should be just as tentative and provisional as our attitude toward quantum wave functions. Introductory relativity texts typically talk about how reference frames are defined with respect to measuring rods and clocks. In an address to the Prussian Academy of Sciences on January 27, 1921, Einstein said:

"All practical geometry is based upon...experience... Suppose two marks

have been put upon a practically-rigid rod. A pair of two such marks we shall call a tract. We imagine two practically-rigid bodies, each with a tract marked on it. These two tracts are said to be 'equal to one another' if the marks of the one tract can be brought to coincide permanently with the marks of the other."

He made a similar point about measurements of time with reference to clocks.

Compare this to a statement of Landau[24] on interpreting the predictions of quantum theory:

"The ... quantitative description of the motion of an electron requires the presence also of physical objects which obey classical mechanics to a sufficient degree of accuracy."

Now, restate Einstein's point in Landau's language:

"The ... [*specification of a reference frame*] requires the presence also of physical objects which obey classical mechanics to a sufficient degree of accuracy."

The definition of reference frames and the interpretation of wave functions are dependent on the same physical objects, subject to the same physical laws. It is physical theory, taken as a whole, that is "relativistic" - not one particular aspect of that theory. Whether through genetic endowment or constant habituation, nature has equipped us with deep intuitions about how the world works. These intuitions, together with the historical path of discovery, have induced us to grant spacetime geometry a special status. Our intellectual apparatus is aimed, largely, at figuring out what we can control, so it is somewhat understandable that nature has not inclined us to more readily consider possible nondeterministic aspects of our world. But, in order to make current theory logically coherent, we need to realize that relativity is rooted as much in the indeterminism that characterizes quantum theory as in the structure of space and time.

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